Publ. Astron. Obs. Belgrade No. 84 (2008), 237 - 240 *Contributed Paper*

DYNAMICS OF LIQUID METAL SURFACE UNDER THE ACTION OF XeCl-LASER PULSES

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Abstract. Processes on surface of liquid metals under the action of XeCl-laser with pulsed energy of 50 mJ are studied. Relaxation time of the surface of melted Gallium and Wood and Gallium-Indium alloys is determined. Minimal relaxation time (about 4 ms) was found to be for Ga and Ga-In alloy. Qualitative description of the processes based on the assumption of capillary waves formation on the melted metal surface was suggested. Suggestion on the selection of liquid metal with minimal surface relaxation time was made based on the suggestion.

1. INTRODUCTION

At present laser-plasma thrusters (LPT) for correction of orbits of micro-satellites on the base of laser evaporation of different materials are intensively developed (see Phipps 2007). By present time first LPT prototypes are studied (see e.g. Phipps et al. 2004, Urech et al. 2004). Targets in the form of rotating metallic rod or moving tape covered with evaporating powder are used in these thrusters. Therewith operation time of such LPT is low due to fast destruction of the targets. Thereupon the use of liquid metals (LM) with low melting temperature should be very promising for great improving of the operating time and reliability of the LPT. In this case the target surface is recovered after a laser pulse due to surface tension forces without any mechanical system feeding evaporating target material into focal area. Relaxation time of the LM surface is important parameter defining maximal pulse repetition rate of the LPT.

It should be noticed that surface dynamics of LM after laser action is studied insufficiently. There is only one paper where relaxation time of surfaces of liquid Tin and Bismuth was measured to be 0,3-1 s after the action of ArF-laser (see Toth et al. 1999).

In this paper processes on a surface of different molten metals were studied using pulses of a XeCl-laser.

2. EXPERIMENTAL TECHNIQUE AND MEASUREMENT METHODS

LM drops were placed on a surface of a nickel plate at pressure p= 0,01-500 Torr. Gallium (melting temperature t_{melt} = 29,8 °C, density ρ = 5,904 g/cm^3), Gallium-Indium alloy (t_{melt} = 16 °C, ρ = 6,235 g/cm^3) and Wood alloy (t_{melt} = 65,5 °C, ρ = 9,72 g/cm^3) were used in experiments. The target temperature during experiments was constant. Radiation of a XeCl - laser with pulse energy of 50 mJ was focused on the target surface by means of a lens and a rotary mirror. The ablation area in the lens focus consisted of two overlapping quadrates with sizes d = 0,4×0,4 mm^2, the radiation power density was $\sim 1,5 \times 10^9$ W/cm^2. Processes on the target surface were monitored by a high-speed CCD-camera (SensisCam). The target surface was photographed through 100 μs with an exposure of 0,5 - 1 μs.

Waveforms of the laser pulse and radiation emission of the laser plasma in different spectral ranges were measured with a FEK − 22 vacuum photodiode. Electrical signals were recorded by a TDS-3034 digital oscilloscope.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Characteristic waveforms of a laser pulse and light emission of laser plasma on surface of liquid and solid metal are shown in Figure 1. Intense peak of the laser radiation reflected from the metal surface was observed during several ns after onset of the laser pulse. This reflected signal sharply disappeared after beginning of the erosion plasma luminescence. Intensity of the reflected signal decreased when liquid surface was irradiated. Besides, replacement of solid surface by the liquid one reduces delay time of laser plasma luminescence onset near the metal surface by 2 - 3 ns. It means that threshold of ablation and plasma formation decreases for targets from liquid metal. Acceleration of the optical breakdown development on the liquid surface can be associated with decrease of reflection of incident laser energy and the lack of energy spent for heating of the metal surface to melting temperature. It was noticed in (see e.g. Götz et al. 1997, Zergioti et al. 1998) that the basic effect on the ablation threshold of liquid targets provides reduction of such thermal losses on target heating and heat conductivity into to the target deep because reflection from the metal surface was suggested to slightly dependent on its state. However, dense cloud of evaporated target material strongly absorbs incident and reflected UV-radiation (see Schittenhelm et al. 1996). In the case of liquid target this cloud is formed during shorter time, and absorption of the laser radiation begins earlier.

Surface of a drop of liquid gallium was recorded at different time moments after the laser pulse. Similarly to (see e.g. Toth et al. 1999, Hopp et al. 2000), changes on the liquid metal surface in our experiments began within 2 - 3 ns after the laser action. Two small cavities are visible on the LM surface by the moment. Their area corresponds to the laser focal spot size. The cavity dimensions vary slowly enough during approximately 0,1 ms. Then the cavities flow together, and fast growth of a hemispheric crater is observed during 0,6 ms. By the instant of 0,6 ms maximum size of the crater reached about 2-3 mm in diameter. Small ledges which have not time

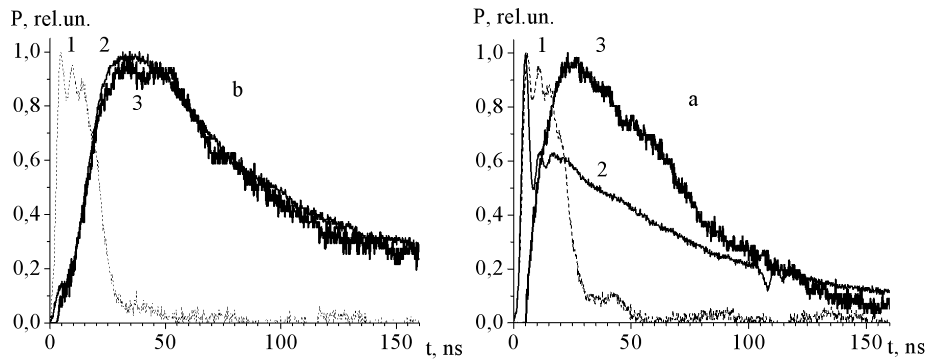

Figure 1: Waveforms of the laser pulse (1) and laser plasma emission pulses on surface of solid (a) and liquid (b) Wood alloy in spectral range 200 - 600 nm (2) and 340 - 600 nm (3) in Neon at p = 370 Torr.

to turn to drops are visible on the crater crest. Then liquid from the crater edges starts to flow downwards, forming a protuberance in the centre. This protuberance gradually grows and during 2 - 2,5 ms fills all crater. Then damped waves with small amplitude run several times on the drop surface. The surface is completely restored in time about 4 ms (see Figure 2). In the case of the Gallium-Indium alloy the recovery time increased approximately on 0,5 ms. Relaxation time increased with the liquid temperature, as well. Process of the surface relaxation of Wood alloy takes about 10 ms.

Relaxation time of the LM surface after the laser action can be qualitatively described in suggestion that surface capillary waves are formed on the liquid metal drop. Velocity of the capillary wave V_K can be written as (see Aleshkevich et al. 2001):

$$V_K = \sqrt{\frac{2\pi\sigma}{\rho\lambda} th \left(\frac{2\pi H}{\lambda} \right)}, \tag{1}$$

where λ is characteristic size of the perturbation on the liquid metal surface after the laser pulse, σ is surface tension and ρ is liquid density, $th\ (\pi H/\lambda)$ is hyperbolic tangent, H is depth of the liquid layer. It is easy to see, that the surface relaxation time is determined by a surface tension and density of the used molten metal. In the case of Gallium (σ = 0,705 N/m) the crater characteristic size is measured to be $\lambda \approx$ 2,5 mm (see Fig. 2), and propagation velocity of the capillary wave is V_K = 0,5 m/s. Accordingly, the surface relaxation time (about 5 ms) is in good agreement with experiment data. Density of Wood alloy is 1,5 times higher and its surface tension is two times lower than those for Gallium. Therefore propagation velocity of a capillary wave on the Wood alloy surface should decrease by a factor of 1,74, and the surface relaxation time increases in the same ratio. In our experiments, the relaxation time of the Wood alloy surface was approximately two times longer than that for Gallium.

Characteristic size of the surface crater strongly depends on the liquid viscosity (see Hopp et al. 2000). Therefore for minimization of the crater size it is necessary to use molten metals with maximal viscosity. Since viscosity sharply decreases at high temperature, the molten metal is necessary to maintain near the melting temperature.

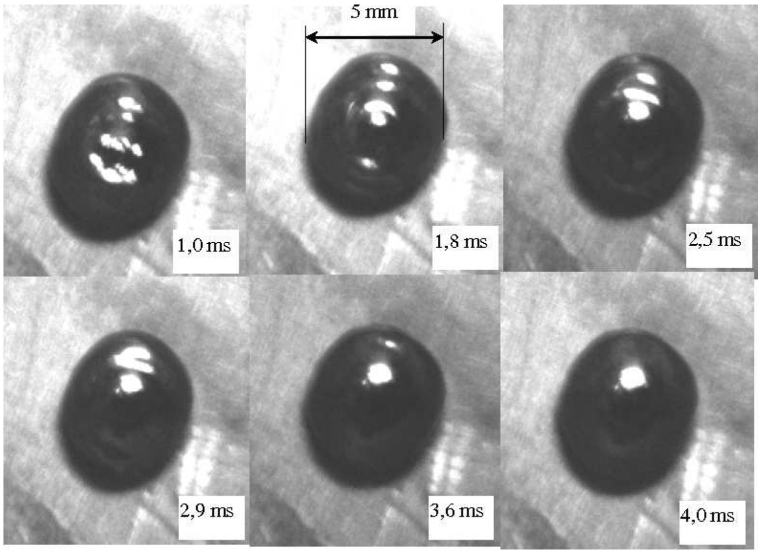

Figure 2: Dynamics of the liquid Gallium surface in the time interval 0 - 3,2 ms after the laser pulse. The exposure time is 1 μs, time interval after the laser pulse is written on each frame.

Basing on the above suggestion it is possible to form demands for selection of LM for LPT. The liquid metal should have high viscosity and maximal ratio σ/ρ. On the basis of this criteria Lithium is one of the best materials.

4. CONCLUSION

The processes on a surface of molten metals after the action of XeCl-laser with pulsed energy of 50 mJ were studied. Relaxation time of surface of some molten metals was measured. Minimal relaxation (about 4 ms) was measured to be for liquid Gallium and its alloy with Indium.

Qualitative description of the processes on the LM surface based on formation of the surface capillary waves is suggested. Demands for selection of LM for LPT are formulated.

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